Plug-and-Play Cartridge Facades: Assessing Energy, Carbon, and Cost in Office Renovations

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Abstract. Renovating existing office buildings is crucial to reducing energy demand and achieving carbon-neutral targets. Among retrofit options, building envelope renovation remains a highly effective way to improve efficiency. However, conventional renovation strategies generally emphasise basic façade improvements, such as window replacement, which may limit the achievable energy reduction. This study evaluates a modular plug-and-play (PnP) cartridge façade system developed to enable rapid installation, easier maintenance, and integration of building technologies in ageing office buildings. A representative office building in Seoul, completed in 1997, was analysed using five years of measured operational data (2020–2024). A calibrated simulation model was developed in OpenStudio and validated in EnergyPlus 24.1, achieving a 2.71% deviation from measured annual energy consumption. Two renovation pathways were compared: (1) a conventional sequential upgrade approach and (2) a smart façade-integrated renovation strategy incorporating modular cartridge systems. Performance was assessed in terms of energy use intensity, carbon emissions, operational energy cost, and life-cycle cost (LCC). The conventional pathway including insulation enhancement, window replacement, solar shading, lighting upgrades, and high-efficiency HVAC systems achieved a maximum energy reduction of 5.6%, lowering annual energy use from 305 to 288 kWh/m2·yr. Carbon emissions decreased from 102.9 to 98.5 kgCO2e/ m2·yr (4.3%), and annual energy costs declined from 40.9 to 39.0 thousand KRW/m²·yr (4.7%). In contrast, the smart renovation approach produced greater reductions. A conventional double-skin façade reduced energy use by 18.1%, whereas the cartridge frame system achieved a 26.0% reduction. With adaptive louvre control, system upgrades, and integration of an air-handling cartridge with a Floor Terminal Unit (FTU), total energy reduction reached 36.8%, reducing consumption to 193 kWh/m2·yr. Carbon emissions decreased to 71.4 kgCO2e/ m2·yr (30.6%), while annual energy costs declined by 29.1%. Although the cartridge façade required 14% higher initial investment than a double-skin façade, it achieved 29% lower maintenance costs and a payback period of approximately 12–13 years. These findings indicate that modular façade systems can provide a practical pathway for achieving deeper energy savings and improved long-term adaptability in existing office buildings.

Keywords. smart skin, cartridge façades, smart renovation, office building, energy simulation, life-cycle-cost

1 Introduction

The 2050 Carbon Neutrality scenario shows the building sector is responsible for 24.6% of South Korea's total greenhouse gas emissions [1]. Office building stock faces a twofold challenge. On the one hand, the national office vacancy rate has risen markedly from 6.6% in 2009 to 12.4% in 2018 [2]. On the other hand, a substantial portion of these buildings is ageing, with many completed over 30 years ago and no longer meeting current spatial and technical standards.

Consequently, the ageing office building stock poses a significant barrier to achieving national energy and carbon reduction targets. These older buildings struggle to meet current performance regulations due to inadequate insulation, single-glazed windows, outdated HVAC systems, and similar issues. In this context, renovation or retrofitting emerges as an effective and sustainable solution.

Many studies have been conducted to identify optimal building renovation strategies to maximise energy reduction [3,4]. Some studies include a broader perspective, such as life-cycle assessment, which evaluates environmental impact [5,6]. Among various renovation strategies, façade renovation is widely recognised as one of the most effective options for reducing energy demand and improving indoor environments [7]. According to H. Lee and G.-S. Choi [8], an envelope retrofit of a public building demonstrated measurable reductions in electricity and CO_2. Another

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study indicated that simulating a double-skin façade retrofit could save 52% of heating and 65% of cooling energy demand [9].

Nevertheless, critical gaps remain in practice, as conventional renovation methods often involve lengthy installation times and limited flexibility for maintenance, upgrades, and adaptation to evolving environmental or technical requirements. Existing façade systems typically lack modularity, hindering rapid replacement, flexibility, customisation, and integration of new functionalities, such as smart building technologies, and program changes. This limitation restricts their ability to respond to diverse functional demands, user needs, and sustainability goals throughout the building's lifecycle.

In response to these challenges, there has been increasing interest in industrialised technologies over the past few decades [10]. Façade envelope modules, for example, minimise on-site construction and require consideration from the start of the design phase. However, even modular solutions still fall short in addressing the full breadth of lifecycle performance needs, particularly with respect to adaptability and long-term technological integration.

To overcome these challenges, a modular, prefabricated, and easily reconfigurable façade system is needed that enables rapid renovation, maintenance, and integration of various technologies. The proposed cartridge-type façade system addresses these needs with its plug-and-play (PnP), drawer-like design, effectively bridging the gap between architectural design and technological integration.

Therefore, this study aims to evaluate the performance of the developed cartridge façade system through simulation. To achieve more realistic results, we modelled an existing office building in Seoul that was built in 1997. Accordingly, this study addresses the following research question: To what extent does the cartridge façade outperform existing façade systems and conventional renovation strategies in terms of energy consumption, CO2 emissions, and energy costs?

The objectives of this paper are: (1) to quantify the performance deficit in façade systems of ageing office buildings and relate it to their energy consumption (2) to evaluate building envelope retrofit scenarios with cartridge façade in terms of energy savings, carbon reduction, and energy cost efficiency. (3) to propose a decision framework for selecting optimal façade renovation strategies tailored to the ageing office building stock in South Korea.

1.1 Definition

The PnP cartridge façade system is designed as a modular, drawer-like configuration, providing a prefabricated PnP system that reduces the time required for building renovations. It also offers straightforward installation, replacement, and reconfiguration options, along with a wide range of technological cartridges, thereby speeding up construction time.

Since it is manufactured in a factory, it meets higher quality standards in a controlled environment and does not require high-skilled labour on site. Through its drawer-like structure, the façade can be easily assembled and detached from the building, significantly simplifying renovation, maintenance, and technical upgrades.

The system exhibits a considerable degree of flexibility by facilitating the integration of various cartridge types. Its modular design allows for the inclusion of multiple types of cartridges, thereby enhancing the building's long-term adaptability to meet evolving environmental, technical, and user-specific demands. Furthermore, the design of the system accommodates extensive customisation, integrating a range of components, including air-handling units, vertical louvres, ICT (Information and Communication Technology) modules, and robotic systems, all within a cohesive structural framework. Consequently, the cartridge façade system serves as a dynamic interface between architecture and technology, thereby promoting sustainable and responsive building design.

1.2 Composition of cartridge facade

The cartridge façade system comprises a bracket, a guide frame, an outdoor skin, an indoor skin with a structure, and various cartridges (Fig. 1). The Size of one module is 1200×1200×3900 mm, which is adapted to the typical office height in South Korea. The brackets are fixed to the structure of an existing building, and the guide frame, which serves as a slide rail for the main frame, is installed on them.

Fig. 1. Composition of cartridge facade

In this study, a vertical louvre, a vertical louvre with dynamic control, and an Air-handling unit (AHU) combined with the FTU system are applied for smart renovation simulation. However, this unit can basically integrate diverse skin cartridge types, for robotics, and ICT cartridges for environmental control have also been developed (see Table 1).

Table 1. The types of cartridges

Types	Description
Cartridge frame	Functioning as a double skin facade
Skin cartridge	Various types of vertical louvres are applicable.
Dynamic control skin cartridge	Upper and lower parts are separately operated, independently control solar radiation and view
Air handling cartridge + FTU	Water-cooled and direct expansion options to accommodate diverse building requirements
ICT cartridge	Managing hardware components and software for environmental controls

2 Methodology

This study examines two renovation pathways to reduce building energy use and carbon emissions. The analysis establishes an empirical baseline by using five years of measured operational data (2020–2024) from an existing office building in Seoul. Two renovation pathways were assessed with performance compared against the baseline in terms of annual energy use intensity (EUI), end-use energy breakdown, carbon emissions, and potential energy cost savings.

The first approach is a conventional renovation strategy that includes enhancements to thermal insulation, high-performance glazing, automated solar shading, and high-efficiency HVAC replacements. The second approach introduces a smart façade-oriented strategy that applies façade-based technologies in a staged manner, supporting dynamic and adaptive performance.

A double-skin façade configuration was additionally modelled to enable direct comparison with the cartridge frame alternative. The results provide a clear performance distinction between the two options. In addition, life-cycle cost (LCC) and payback time were assessed to evaluate the cost-effectiveness of the cartridge façade compared to a double-skin one. Overall, these analyses provide a comparative understanding of how traditional renovation methods and façade-integrated strategies influence whole-building energy performance over time.

2.1 Building information

The target building is an office building located in Seoul, South Korea. Completed in 1997, it features six basement levels and twenty-six stories. The site area measures 2,893 m^2, while the total gross floor area is 40,157 m^2. The structural system of the building is reinforced concrete, and a floor area of 21,252 and 25,455 m^2 has been designated for simulation purposes.

2.2 Simulation framework

2.2.1 Baseline model development

A representative baseline energy model was developed in OpenStudio and simulated in EnergyPlus 24.1. The model incorporated actual construction details, operational schedules, and HVAC system configurations.
Weather input was based on the Seoul Typical Meteorological Year (TMY). The selection reflects the primary objective of this study: to evaluate the relative energy performance improvements attributable to renovation technologies rather than year-specific climate variability. The use of TMY reduces the sensitivity of short-term climate anomalies and ensures consistency in scenario-based comparisons.

2.2.2 Operational standardisation and model assumptions

To establish a consistent baseline for comparative analysis, operational conditions were standardised prior to calibration. Internal load densities were set as follows: occupancy at 0.15 persons/m² (office) and 0.05 persons/m² (corridors/restrooms); lighting at 6.7 W/m² (office) and 7.5–10 W/m² (corridors/restrooms); and office equipment at 20 W/m². Cooling and heating periods were defined as May 15–October 10 and November 20–March 15, respectively, with daily HVAC operation from 07:00 to 19:00. Temperature setpoints were fixed at 24 °C for cooling and 20 °C for heating.

2.2.3 Calibration procedure

The simulation model used a deterministic iterative trial-and-error approach. Calibration targets were set at ±10% for monthly error and ±5% for annual error. Key uncertain parameters adjusted during calibration included HVAC operating schedules, heating and cooling setpoints, internal loads (lighting, equipment, and occupancy), equipment efficiencies, part-load characteristics, and holiday operations. The final calibration model achieved a deviation of 2.71% in annual total energy consumption relative to measured data, confirm, confirming its reliability for simulation-based evaluation. The total energy includes heating, cooling, ventilation, lighting, and office appliances. This procedure prevents non-representative operational anomalies and provides a consistent reference for evaluating renovation-driven energy performance improvements, thereby establishing a technology-driven performance comparison framework. Table 2 shows the essential information for the building simulation.

Table 2. Simulation information

Classification	**Baseline**	**Conventional renovation**	**Smart renovation**
Conditioned area	21,252 m^2	21,252 m^2	25,455 m^2
Wall	U = 0.399 W/ m^2·K	U = 0.130 W/ m^2·K	U = 0.130 W/ m^2·K
Roof	U = 0.385	U = 0.115	U = 0.115
Floor	U = 0.313	U = 0.150	U = 0.150
Windows	U = 2.75 SHGC =0.703 (WWR=27.7 %)	U = 1.02, SHGC = 0.4 (WWR=27.7 %)	inner U = 1.02 SHGC = 0.4 (WWR=54.2%) outer U = 5.70, SHGC = 0.7

2.3 Conventional renovation scenario

The Conventional Renovation mainly focuses on a passive energy conservation concept, aiming to improve the thermal resistance of the building envelope. It is designed to represent a gradual upgrade sequence typically implemented in existing office buildings. In this approach, five retrofit measures were analysed to evaluate their relative and cumulative impacts on overall building energy performance.

First, thermal insulation of exterior walls, roofs, and floors was enhanced beyond current Korean building energy code standards to quantify potential reductions in heating and cooling energy demand. Second, the window upgrade was from U-value 2.84 and SHGC 0.703 to U-value 1.02 and SHGC 0.4. Third, automated sun shading control systems were introduced to respond to solar irradiance, thereby minimising excessive solar gains while preserving adequate daylight levels. Fourth, a lighting upgrade indicates replacing lights with LEDs. Finally, the HVAC system was upgraded by replacing the existing pumps and fans with IE3-grade high-efficiency motors, resulting in reduced auxiliary energy consumption and enhanced overall system performance.

2.4 Smart facade renovation scenario

The Smart Renovation project was designed to explore façade-based and system-level solutions that support energy-responsive and user-centred buildings. This approach involved a stepwise process in which the renovation pathway integrates façade-based adaptive solutions with system-level improvements. Specifically, the insulation capacity of the renovation model was enhanced, and additional smart technologies were introduced at each stage to improve thermal performance, solar control, and operational efficiency. To compare the differences between the typical double-skin façade and the cartridge frame-only design, the double-skin type was included in the smart renovation category.

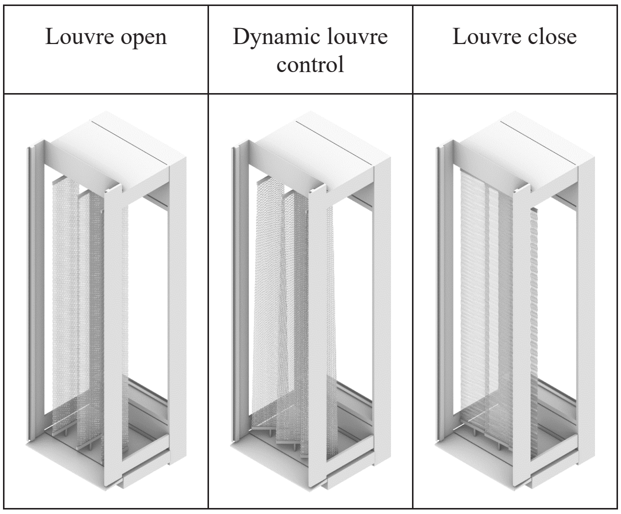

Fig. 2. Vertical louvre controls

In the first stage, cartridge-frame units were implemented to create building simulations featuring improved insulation and high-performance windows. These enhancements exceed the current requirements set by Korean building energy codes. In the second stage, vertical louvres were added to the frame to control sunlight. Fig. 2 illustrates the dynamic control louvre types. This addition enables adjustments to solar heat regulation and manages the amount of daylight entering the building. The third stage focused on energy-efficiency improvements. We added inverter circulation pumps and high-efficiency motors to minimise excess energy consumption and enhance system performance. This stage also included upgrades to system efficiency, further reducing auxiliary energy use. Finally, the Floor Terminal Unit (FTU) was incorporated with an air-handling cartridge within a façade frame to improve indoor environmental quality and thermal comfort.

3 Results

The baseline model was created in OpenStudio and simulated in EnergyPlus 24.1. The baseline model results were compared with the building's actual energy use over a 5-year period from 2020 to 2024. The comparison showed only a 2.71% deviation from the measured data, confirming the reliability of the model.

3.1 Conventional renovation

In the conventional renovation scenario, only limited construction measures were implemented to preserve the existing exterior of the buildings. As a result, deep façade retrofitting was not included in the comparison, and only window replacement was assessed. Instead, a double-skin façade was incorporated into the smart renovation simulation to allow for a direct comparison with the cartridge frame option. Table 2 summarises the simulation results for this scenario. Energy consumption, costs, and carbon emissions are presented on a per-square-meter basis to clearly illustrate relative performance improvements.

Table 3. Results of conventional renovation simulation

Stages	Energy reduction gap (%)	Energy consumption (kWh/m²·yr)	Energy cost (1.000KRW/ m²·yr)	Carbon emissions ($kgCO_2e$/ m²·yr)
(a)	-	305	40.9	102.9
(b)	0.6	303	40.7	102.5
(c)	3.3	295	39.9	100.7
(d)	3.6	294	39.7	100.4
(e)	4.5	291	39.3	99.4
(f)	5.6	288	39.0	98.5

(a) Baseline
(b) Enhancing the insulation layer
(c) Enhancing the insulation layer + Window upgrade
(d) Enhancing the insulation layer + Window upgrade + Addition of sun-shading
(e) Enhancing the insulation layer + Window upgrade + Addition of sun-shading + Light upgrade
(f) Enhancing the insulation layer + Window upgrade + Addition of sun-shading + Light upgrade + High-efficiency HVAC

3.1.1 Energy consumption

The conventional renovation approach results in relatively modest energy savings. The baseline annual energy consumption of the building was 6,474,852 kWh, which equates to 305 kWh/m² per year. Enhancing the insulation layer reduced energy consumption by 0.6%, bringing it down to 6,435,520 kWh. Window upgrades achieved a more significant reduction of 3.3%, resulting in an annual consumption of 295 kWh/m². The addition of a shading device, implemented as the third stage of the conventional renovation, led to a further 3.6% decrease, though this was not a dramatic improvement. The lighting upgrade produced a 4.5% reduction in energy use. Finally, the HVAC system upgrade had the greatest impact, reducing annual energy demand by 5.6% to 288 kWh/m²·yr. Overall, the combination of window and HVAC upgrades proved to be the most effective conventional renovation method.

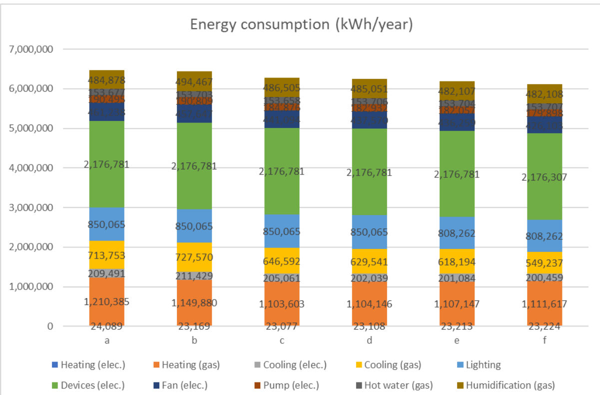

Fig. 3. Conventional renovation energy use per category

3.1.2 CO_2 emissions

The existing building emits 102.9 $kgCO_2e$/m²·yr. The conventional renovation pathway indicates modest savings: upgrading the insulation layer reduced carbon emissions by 0.4%, while window replacement and the addition of sun-shading achieved reductions of 2.1% and 2.4%, respectively. The implementation of a high-efficiency HVAC system resulted in a total reduction of 4.3% relative to the baseline, lowering emissions to 98.5 $kgCO_2e$/m²·year.

3.1.3 Energy costs

Relative to the baseline, electricity consumption decreases modestly across all cases, ranging from 0.1% with improved insulation to approximately 2.8% with the HVAC upgrade. Gas consumption shows a similar trend, with the largest decrease observed in the HVAC upgrade scenario. As a result, the total annual energy cost declines from 869,704,000 to 828,757,000 KRW, representing an overall reduction of 4.7% relative to the baseline. On an annual cost-per-square-meter basis, energy costs gradually decrease from 40.9 to 39.0 thousand KRW/m²·yr across the renovation stages.

3.2 Smart renovation

Smart renovation was categorised into façade-centric measures with advanced integration, while the lighting and HVAC upgrades were treated as system-only renovation methods. The simulation results reveal the cumulative impact of each renovation stage (see Table 4). In particular, the sequential implementation of the cartridge systems, lighting control and upgrade, and HVAC upgrade demonstrates a clear additive effect, allowing the relative contribution of each measure to be quantitatively distinguished.

Table 4. Results of smart renovation simulation

Stages	Energy reduction gap (%)	Energy consumption (kWh/m²·yr)	Energy cost (1.000KRW/m²·yr)	Carbon emissions (CO_2e/m²·yr)
(A)	-	305	40.9	102.9
(B)	18.1	250	34.4	83.8
(C)	26.0	226	31.6	77.2
(D)	26.7	223	31.4	76.6
(D-1)	27.3	222	31.1	76.3
(D-2)	27.9	220	30.9	75.8
(E)	28.8	217	30.5	74.7
(F)	30.1	213	30.0	73.5
(G)	36.8	193	29.0	71.4

(A) Baseline
(B) Double-skin facade
(C) Frame
(D) Frame + Vertical louvre
(D-1) Frame + Vertical louvre (half open)

(D-2) Frame + Vertical louvre (close)
(E) Frame + Vertical louvre + Lighting upgrade & control
(F) Frame + Vertical louvre + Lighting upgrade & control + HVAC upgrade
(G) Frame + Vertical louvre + Lighting upgrade & control + HVAC upgrade + AHU & FTU

3.2.1 Energy consumption

Fig. 4 shows smart renovation energy use per category. The first intervention involved installing a cartridge frame that functions as a double-skin façade, resulting in a 26.0% reduction in total energy use, which equates to 5,741,476 kWh or 226 kWh/m² per year. In comparison, a typical double-skin façade saves only 18.1% of energy usage relative to the baseline model. By incorporating a skin cartridge with fixed vertical louvres, energy savings increased to 26.7%. Introducing dynamic louvre control further enhanced the reduction to 27.3%. Additionally, fully closing the louvres provided a slightly better improvement, achieving a 27.9% reduction compared to the baseline.

Following this, an HVAC system upgrade led to a 30.1% reduction in total energy use. The most significant improvement came from integrating an air-handling cartridge with a Floor Terminal Unit (FTU) system, resulting in a 36.8% reduction. Among all stages of the renovation, the integration of the FTU provided the greatest incremental benefit, contributing an additional 6.7% decrease in energy consumption.

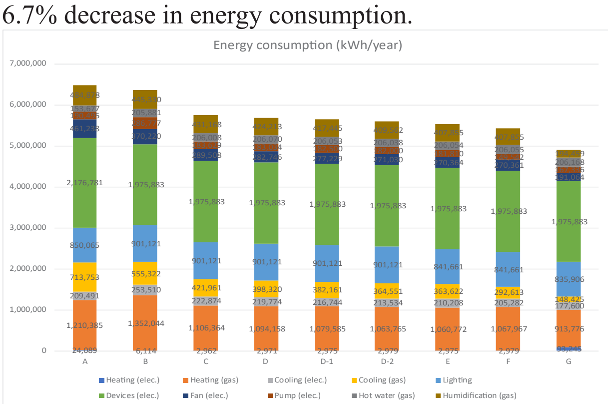

Fig. 4. Smart renovation energy use per category

3.2.2 CO_2 emissions

Table 5 shows that CO_2 emissions decrease as operational energy use declines. Compared to the baseline, both electricity and gas consumption are reduced across all scenarios, with the most significant absolute reductions observed under the FTU-based configuration. Carbon emissions drop from 102.9 to 71.4 $kgCO_2e/m^2$·year, representing a maximum decrease of 30.6%. Measures that incorporate a cartridge frame with vertical louvres yield consistent improvements, ranging from 24.9% to 26.6% reduction in emissions, while an HVAC upgrade results in a 28.5% decline. When more advanced optimisation measures were implemented in Stages E and F, the overall reduction increased further. These results demonstrate that smart renovations with façade-integrated systems outperform traditional measures. By combining smart envelopes with an active system, greater efficiency is achieved, along with reduced emissions and long-term adaptability for sustainable building operations.

3.2.3 Energy costs

Operational energy costs consistently declined across all stages of performance enhancement. Compared to the baseline condition (40.9 thousand KRW/m²·yr), Stage B reduced annual energy costs by approximately 15.9%. For Stages D through D-2, total cost reductions increased to 23–24%, reflecting the cumulative impact of successive façade and control upgrades. Further optimisation in Stages E and F resulted in reductions of 25.4% and 26.7%, respectively. Under the Stage G scenario, annual energy costs decreased by approximately 29.1% relative to the baseline, reaching 29.0 thousand KRW/m²·yr. These results indicate that deeper levels of energy performance not only reduce operational consumption but also significantly enhance economic outcomes, highlighting the value of integrated façade-system renovation strategies.

3.3 Plug-and-play cartridge façade renovation cost analysis

Cost-effectiveness is the most important aspect in building renovation, besides energy reduction. In this study, the cost analysis includes not only energy-saving costs but also life-cycle costs and payback time. Two different areas were used to calculate cost analysis: façade and net areas. Regarding façade renovations, the façade area was used to calculate renovation costs per square meter, and the net area was applied to compare facility-related renovation costs. This is because façade renovation costs depend heavily on the façade area rather than the net area, and the cost per square meter can vary widely depending on a building's volume.

3.3.1 Life-cycle-cost

Life-cycle cost comprises three categories: initial investment, maintenance, and disassembly. When the façade needs partial replacement or is damaged, a conventional curtainwall system requires extensive replacement and rework of piping and equipment to address the issue, resulting in longer maintenance duration and higher cost. In contrast, a modularised cartridge façade system can take the part that only needs replacement or a damaged part. Moreover, it does not require extensive plumbing rework, as the drawer-like mechanism allows replacing or repairing only the damaged module. This removes the need to dismantle entire sections or reinstall complex piping systems, ensuring faster and more cost-effective maintenance.

Regular inspection also requires fewer devices, less labour, reduced time, and higher maintenance accessibility.

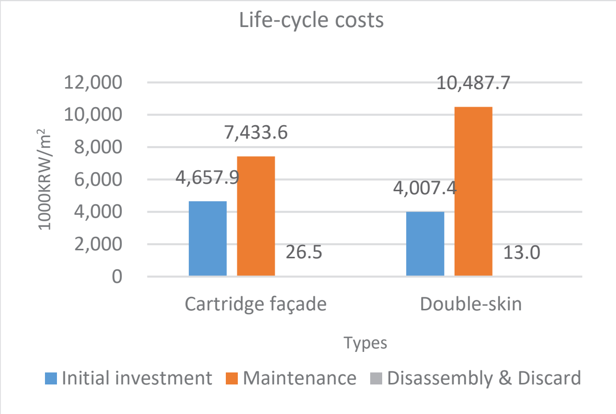

Fig. 5. Comparison of LCC between the cartridge and the double-skin façade

Fig. 5 compares LCC between the cartridge and double-skin façades. Overall, maintenance costs account for the largest share of total life-cycle costs. Specifically, the cartridge façade system has an initial investment cost about 14% higher than that of a double-skin façade. However, the cartridge façade could save approximately 29% in maintenance costs compared to a double-skin façade. Although the disassembly and disposal costs of the cartridge façade double the price, they constitute the smallest share of the LCC. Because the envelope, louvre, and AHU are integrated into a single modular component, the overall installation time can be reduced. In total, 16% of the LCC difference occurs between the double-skin and cartridge façades.

3.3.2 Payback time

For the payback time calculation, energy reduction, increased rentable area, and simplified maintenance aspects are considered. Additionally, depreciation was deducted from the total returns.

In Fig. 6, the payback analysis indicates that annual net income remains constant over the 20-year evaluation period, whereas cumulative net profit increases linearly from an initial negative value. The cumulative curve begins at approximately 11.5 years and moves toward zero, reflecting the gradual recovery of the initial investment. The breakeven point occurs between the 12th and 13th years, where cumulative net profit shifts from -157 million KRW to +96 million KRW. After this point, the slope continues to accumulate positively, reaching approximately 2.1 billion KRW by the 20th year. This trend demonstrates an annual financial return and a payback time of roughly 12-13 years.

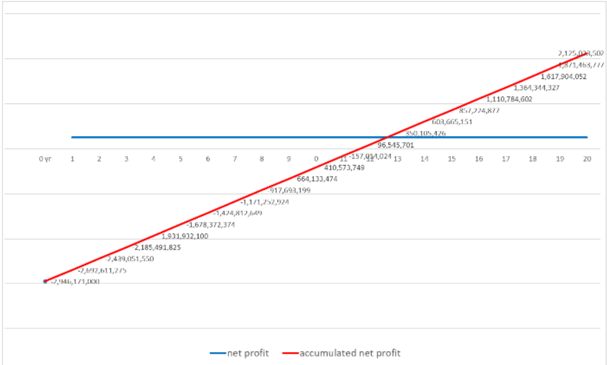

Fig. 6. Payback time of the new façade system

4 Discussion

The simulation results indicate that the PnP cartridge façade improves energy performance while reshaping the interactions among envelope design, construction methods, and operational efficiency. Unlike conventional renovation strategies, which often focus solely on insulation or glazing upgrades, the cartridge façade appears to optimise both thermal and economic outcomes simultaneously. Since high-tech systems are costly, investment costs can be high; however, the system has greater value when LCC is considered.

The economic savings are achieved especially through its modular and industrialised characteristics. In general, the focal point of the modular system can reduce LCC. One study found that modular construction methods can reduce project duration by 30-50%, resulting in overall cost reductions of 20% [11]. According to the Construction Economy Research Institute (CERI) analysis, the cartridge façade system reduced LCC by 16.47% and achieved around a 20% reduction in construction duration, compared to a conventional double-skin façade. The LCC analysis clearly shows a significant reduction in maintenance costs.

The PnP, as an off-site industrialised system, enables quicker, easier assembly. According to J. Torres, et al. [12], the PnP system can reduce execution time by 40-50% quicker than a conventional façade system. But in this study, the façade is added to an existing façade without demolishing the structure, whereas when we calculate the renovation time, it includes demolishing the existing façade and then adding the PnP façade, which can reduce construction time by 20%.

The PnP cartridge façade system significantly enhanced the building's energy performance, resulting in 36.8% energy savings in this study. While a conventional (minor) renovation achieved only 5.6% energy reduction. This conventional model showed a significantly lower energy-saving potential than previous studies. For example, a study elaborated actual energy-use data from Korean public buildings after insulation and window replacement retrofits. The average monthly electricity use dropped by 8.0-14.7% [8]. Another simulation-based study investigated improvements in the thermal insulation properties of window glass, which could reduce energy consumption by up to 22% [13]. In this simulation-based study, the energy-saving rate of the conventional renovation did not dramatically decrease, ranging from 0.6 to 5.6%, whereas the smart renovation sequence achieved energy savings of 26.0-36.8%. The reason is that the conventional renovation range was limited to strategies that maintained the building's appearance as much as possible. Following the limited condition, carbon emissions and cost reductions were small.

The simulation showed that the frame-only cartridge façade achieved about 8% greater energy savings than the double-skin façade. Although both systems operate on similar principles, their performance differed because the cartridge frame functions as an independent façade element rather than a conventional double-skin configuration. This suggests that design integration and system structure influence overall efficiency. Further research is needed to clarify why similar façade concepts result in different reductions in energy use, carbon emissions, and energy costs.

5 Conclusions

This study evaluated a plug-and-play (PnP) cartridge façade system by simulating a 1997 office building in Seoul. Compared with conventional renovation strategies, the proposed system achieved substantially greater improvements in energy, carbon, and cost performance. The results indicate that incremental upgrades alone have a limited impact on ageing office buildings.

The PnP cartridge façade reduced total energy use by 36.8%, energy costs by 29.1%, and carbon emissions by 30.6%, demonstrating its potential as a scalable deep-retrofit solution. Beyond performance gains, the study shows that the cartridge façade offers practical advantages in modularity and functional integration. Within a standardised frame, it can incorporate shading devices and façade-based HVAC components, allowing flexibility while maintaining system consistency. This approach shifts façade renovation from isolated component upgrades toward integrated performance-based transformation.

Overall, the findings highlight the importance of combining envelope improvement, energy management, and economic feasibility in renovation projects. Following its full-scale application in Seoul in March 2025, future research will examine indoor environmental performance, occupant comfort, and ICT-based personal environmental control strategies.

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